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Eye/Sensor Protection Against Laser Irradiation Ablative Mirror Devices: A Materials Assessment

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The potential of the ablative mirror concept as an eye/sensor protection system is assessed from a materials science perspective. Realistic operating parameters for the ablative mirror device are determined through examinations of the critical device components. Using these operational parameters and a derived model of laser-surface interactions, the response of different mirror materials is examined. Based on the measured material responses from research literature and our calculated values, we conclude that the ablative mirror concept is not a feasible method of eye protection using typical mirror materials (assuming a device optical gain of 10^5 and a minimum material reflectivity of 70%). Analysis of the interaction between laser irradiation and material surfaces resulted in the identification of a number of important material parameters that can be used to guide material development and identify promising new mirror materials. Areas for future research are also suggested.

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EYE/SENSOR PROTECTION AGAINST LASER IRRADIATION ABLATIVE MIRROR DEVICES: A MATERIALS ASSESSMENT

INTRODUCTION

As the distribution of laser systems throughout modern society continues to increase, so do potential encounters with human eye damaging radiation. Protecting eyes from both direct and indirect exposure to laser radiation is a difficult and growing challenge because of the wide range of electromagnetic energy available in common laser systems (e.g., wavelength and pulse lengths) and the extreme sensitivity of the eye. Frequency agile systems which can protect against a wide range of incident light intensity and have a fast response (nanosecond regime) are needed for use against both continuous wave (CW) and pulsed laser irradiation. The development of such a system from concept to deployable device requires the collaborative efforts of scientists from many fields.

In order to be a viable eye protection element, a device must be capable of responding at incident energy densities lower than the damage threshold of the eye. Commonly accepted eye damage thresholds indicate that the device must be able to respond to about 0.5 $\mu J/cm^2$ of incident light in a nanosecond time frame (approximately 500W/cm^2 on a power scale).[1,2] To overcome this sensitivity issue, most proposed passive eye protection devices require a focal plane where the incident light is concentrated onto an active surface. Two examples of such an approach are the "optical switch" and the "optical fuse". In the "switch" system, a nonlinear optical material is employed whose index of refraction or absorption/reflectivity is affected by the focussed incident light. Many researchers are working on developing nonlinear optical materials for use in such a device. However, while dramatic improvements in material response are being reported, the nonlinear optical response of state-

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of-the-art materials is still inadequate for eye protection and/or is only active over a limited frequency range. The "fuse" system employs a thin reflector (mirror) at the focal plane which has been designed to fail/ablate at an irradiance threshold below that of eye damage. It is this second system, also known as the sacrificial mirror concept, that is the subject of this report.

In this paper, an assessment of the potential of the sacrificial mirror concept as an eye (and perhaps sensor) protection system is made from a materials science perspective. This is accomplished by first briefly discussing the basic operating principles of the device, in order to identify and define important device and material parameters, and then reviewing recent developments in laser-surface interactions of potential mirror materials. Finally, areas of future interest are defined.

SACRIFICIAL MIRROR

CONCEPT DESCRIPTION

A schematic view of a generic sacrificial mirror device is depicted in Figure 1. The incident radiation passes through an objective lens which focusses the light onto the sacrificial mirror. At low incident intensities the sacrificial mirror reflects the incident light towards the eye by way of a correcting lens system. At sufficiently high incident intensities the sacrificial mirror ablates, interrupting the optical path to the eye. The incident energy is then absorbed by the beam dump which can be the mirror substrate or an absorptive block located behind a transparent mirror substrate. The beam dump can also be envisioned as a detector which, once triggered, activates an additional, independent protection system. Care must be taken to insure that the beam dump (mirror substrate) is itself not sufficiently reflective, while still optically flat, that it directs damaging light intensity to the eye. One way to avoid this situation is to apply the reflective optical fuse layer (mirror) to the back surface of a transparent support and place an absorbing beam dump behind and at an angle to that reflective coating. In this configuration, the destruction of the mirror results in a direct path to the beam dump with a minimum amount of reflected light directed back towards the eye.

Since the region of the mirror that is damaged by the incident radiation is small, a few microns in area, the mirror needs to be moved only a small distance in order to restore vision. With an appropriate design, Figure 2, it should be possible to rapidly mechanically reposition a new location on the

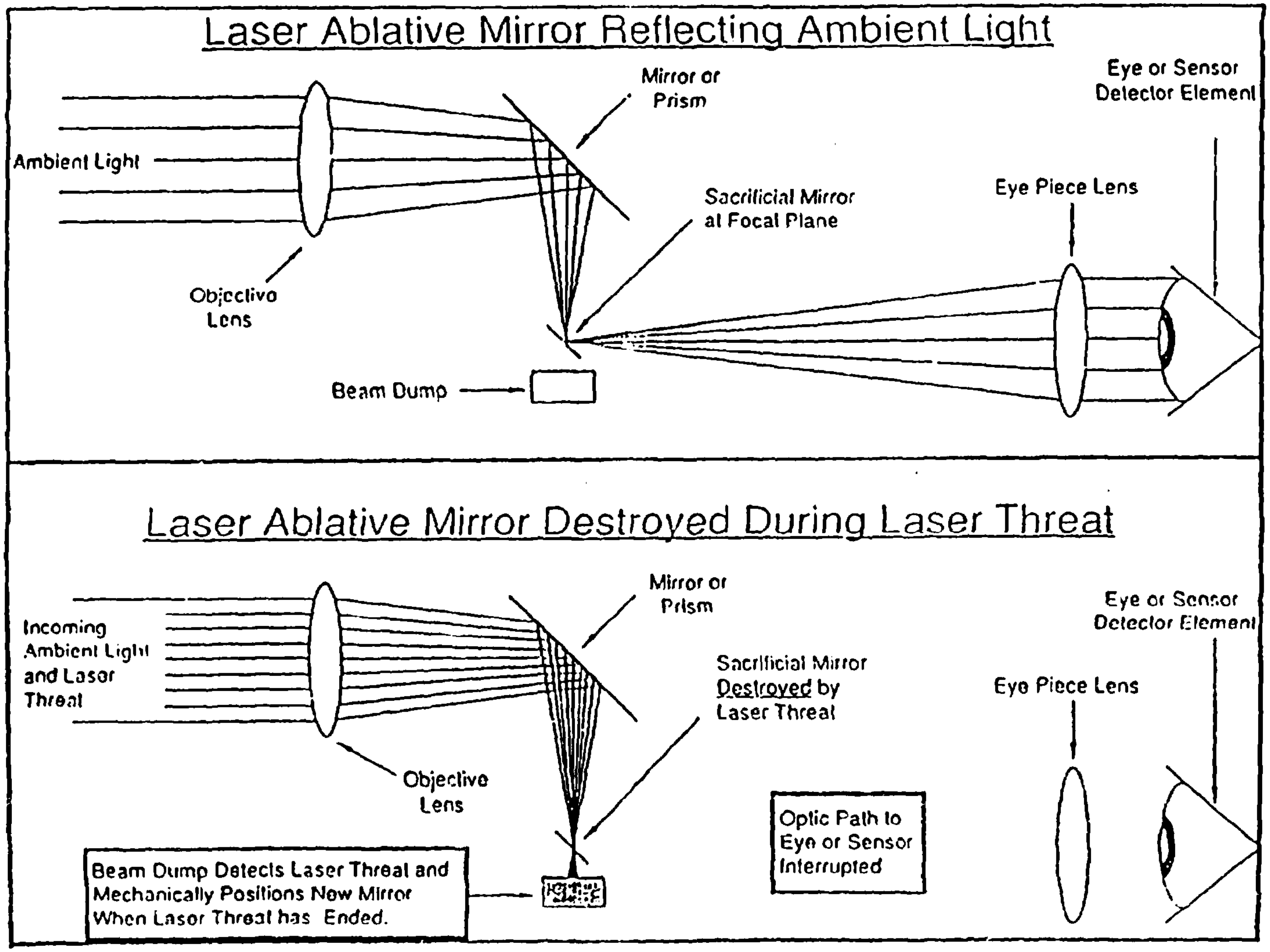

Figure 1a. A schematic diagram of the basic optical system for a mirror/optical-fuse device for eye protection against laser irradiation.

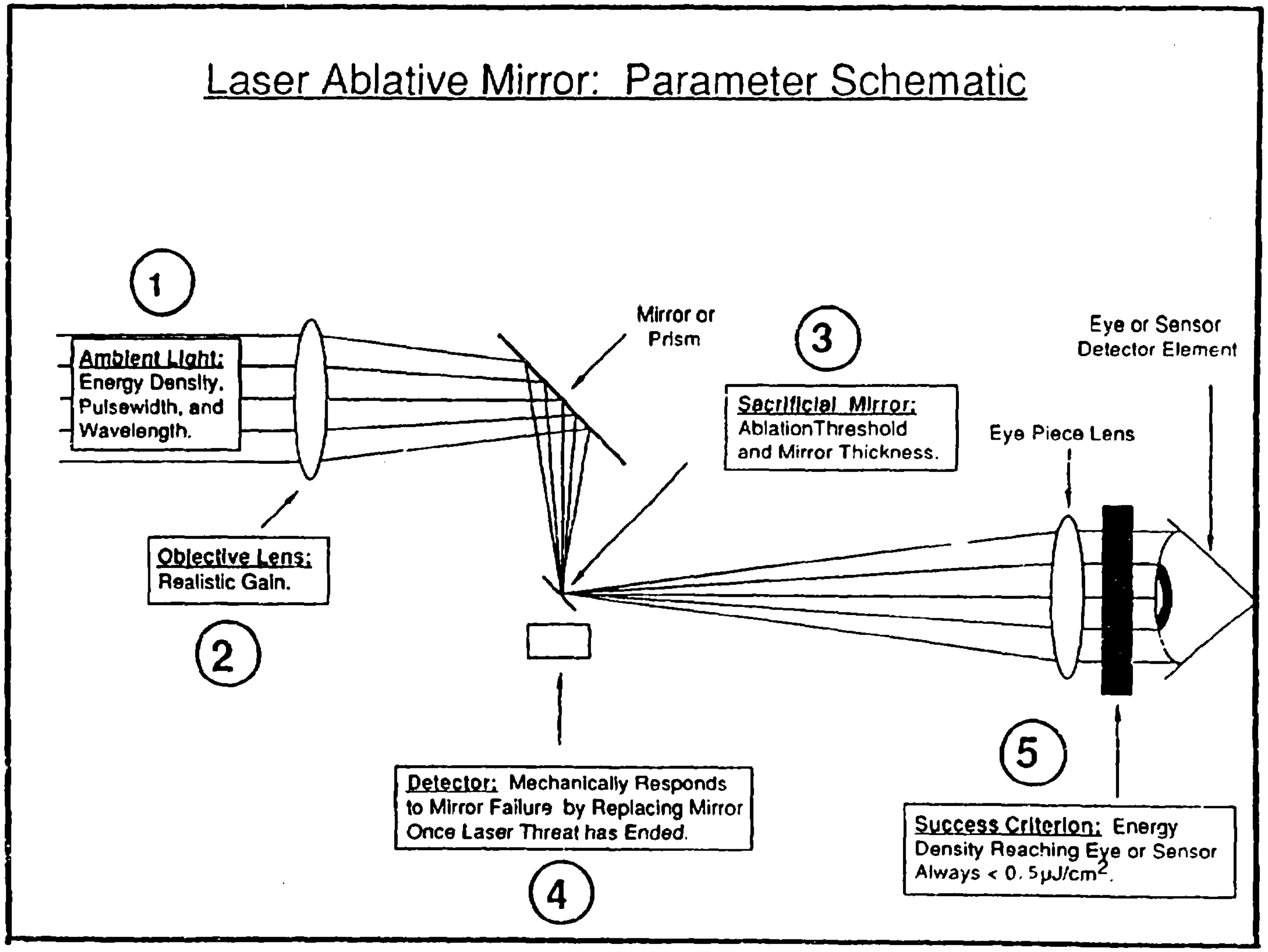

Figure 1b. A schematic diagram of the basic optical system for a mirror/optical-fuse device detailing important component operating parameters.

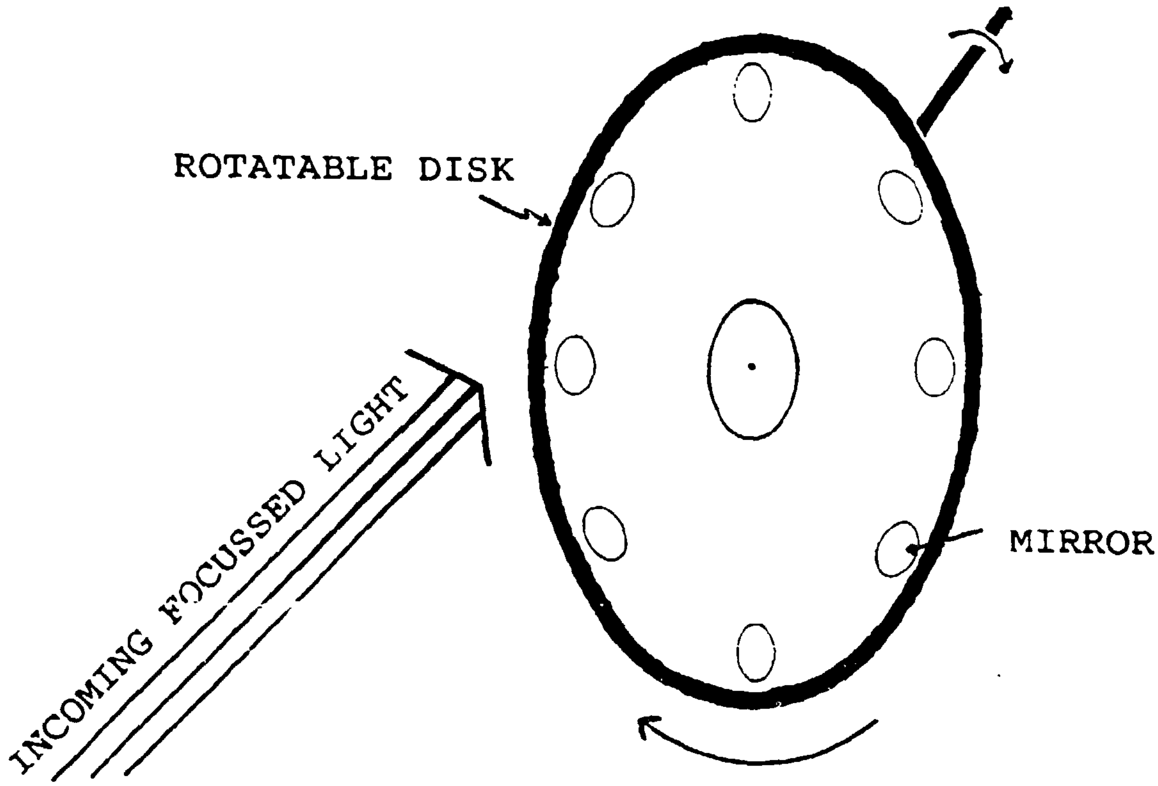

Figure 2. A sketch of one mirror/substrate design which would allow for easy and rapid repositioning of a the mirror surface after irradiation damage and repositioning of a new mirror surface once irreparable damage has occurred.

sacrificial mirror into the optic path. That is, to reset the "optical circuit breaker" and thereby quickly reestablish vision. Contingencies must also be made for when the mirror has become ablated in several spots, degrading performance, i.e., the ability to reposition a new mirror into the optical path (Figure 2).

To protect the eye without the use of a focal plane requires a material that can respond to an incident energy density less than 0.5 $\mu J/cm^2$ in a nanosecond time frame. However, most metal mirror materials have intrinsic damage thresholds, for an optically pure surface, in the range of 1 to 4 J/cm^2 for nsec pulses (Table 1).[3] Thus, the focal plane is seen to be an indispensable component of the sacrificial mirror concept. (To use a mirror design requires an optical system, so the inclusion of a focal plane is not an unreasonable or overly complicating design issue.)

Perhaps the most important device parameter in the sacrificial mirror concept is the optical gain available from the objective lens (Figure 1). Typical off-the-shelf components can achieve gains on the order of 10^5 to 10^6 with higher quality components capable of gains of approximately 10^8 to 10^9. (These optical gains are calculated by ratioing the area of the input lens to the area of the focussed spot. A spot diameter of 10 μm is assumed for the off-the-shelf components while a spot diameter of 1 μm is used for the high quality components. The 1 μm spot size is reported in an optical component catalog for a laser system condenser lens with a working distance of 6 mm.) Unfortunately, there is a trade-off between the optical gain, the field-of-view or device acceptance angle, light gathering capacity, frequency agile response and the optical system size. That is, large gains and acceptable viewing angles (assumed here to be at least 20°) are not compatible unless

TABLE 1

Metal	LIDT (J/cm^2)	Pulsewidth, γ (ns)	Wavelength, λ (μm)
Silver Ag	60	100	10.6
	370	2000	10.6
	220	100	3.8
	200	100	2.7
	11	9	1.06
	37	500	0.492
Copper Cu	12	1.4	10.6
	17	28	10.6
	69	50	10.6
	95	90	10.6
	70	100	10.6
	56	100	10.6
	60	100	10.6
	480	2000	10.6
	230	100	3.8
	190	100	2.7
	90	9	1.06
	2-14	20	1.06
	11	500	0.492
Gold Au	43	100	10.6
	21	100	10.6
	37	100	10.6
	275	2000	10.6
	138	100	3.8
	123	100	2.7
	6	9	1.06
	13	500	0.492
Molybdenum Mo	8	100	10.6
	370	2000	10.6
	24	500	0.492
Aluminum Al	0.7	1.4	10.6
	40	100	10.6
	14	100	10.6
	8	500	0.492

Table 1. Measured laser-induced damage thresholds (LIDT) for common mirror materials.[4-10]

physically large optics and optical paths are used, which, in turn, severely limit the utility of the protection device. In addition, spherical and chromatic aberrations limit the gain available in lenses designed for panoramic viewing. Therefore, for the purposes of this discussion, we assume optical gains of 10^5 to 10^6 (which coincidently is similar to that of the eye itself) with acceptable fields-of-view (about 20°) are possible in deployable devices composed of typical optical components. This choice of device parameters results in a maximum material damage threshold of approximately 0.5 J/cm^2 at the focal plane for exposure durations of about 10^{-9} seconds (approximately 10^8 W/cm^2). This damage threshold is at the exact limit for eye damage and viable eye protection devices should incorporate a safety margin of at least several factors to an order of magnitude beyond this minimum protection limit in order to insure eye safety.

More elaborate optical systems may be able to dramatically affect the material threshold limit by decreasing the assumed focussed spot size and/or increasing the input aperture, e.g., assuming an optical gain of 10^9, the maximum material damage threshold becomes 500 J/cm^2. However, for the purposes of this report, we assume the material damage and device values given above. We also will assume that the minimum acceptable reflectivity of the mirror system is 70%. That is, a 30% reduction in ambient light reaching the observer's eye is all that we allow. If a greater reduction in ambient transmission is acceptable, a proportionately lower threshold for "optical fuse failure" would be obtained. For comparison, typical sunglasses absorb about 90% of visible light.

MIRROR MATERIALS

The maximum damage threshold of the sacrificial mirror estimated in the preceding section for successful eye protection, 0.5 J/cm^2, is several times more sensitive than the measured damage threshold of pure aluminum in the visible spectral region, one of the most easily ablated and highly reflective of several common mirror materials (see Table 1). In order to assess the potential for achieving the maximum damage threshold in common as well as uncommon elemental metal mirror materials it is first necessary to identify the important material parameters and how they affect the damage threshold. To accomplish this, we briefly examine laser-target interactions and the corresponding damage mechanisms. Using the designated material parameters, we then develop a damage model to assist in defining areas of future research for improving mirror "fuse" performance.

LASER-TARGET INTERACTIONS

INTRODUCTION

In general, laser-produced damage in thin films results from either dielectric breakdown induced by the electric field of the laser radiation or by the thermal absorption of laser energy by the film. The ablative mirror materials under consideration are metals and therefore exclude the more wavelength-selective dielectric mirrors. Laser-produced damage in metallic thin film mirrors such as Al, Ag, Cr, Cu, Au, Mo and Rh, will occur by a thermal absorption mechanism.

Thermal damage begins with the absorption of the incident photon energy

into the electronic system of the material. This energy is completely thermalized (i.e., thermal equilibrium is achieved) in the nanosecond time range,[11,12] although melting has been observed over picosecond pulse lengths in silicon and graphite.[13,14] If the thermal energy density is sufficiently high, on the order of the binding energy of the atoms in the crystal lattice (1-10 eV/atom, Table 2), and lasts for a sufficiently long time ($>10^{-12}$ sec), material ablation can occur.

Ablation is the photo-induced ejection of material from the surface (front or back) of a target. Laser ablation is of interest in many different areas of basic research and technological development ranging from materials processing, to surgery, to lithography. The different fields of interest are illustrated in Figure 3, where a typical rate of material removal per laser pulse is plotted versus power density.

Many experiments involving the laser ablation of surfaces of solid targets have been reported in the literature including the etching of semiconductors[15], the ablation of polymers[16] and biological tissue[17], and the laser-induced desorption of adsorbates on metals or semiconductors[18]. It is clear from these studies that ablation from a solid target is not simply modeled.[15-18] This is due, in part, to inhomogeneities or extrinsic effects which tend to modify the apparent on-target power density distribution in the laser pulse, producing local higher power and energy densities: a "spiky" beam.[19,20] These inhomogeneities include voids, absorptive inclusions, surface cracks and abrasions and impurities.

Difficulties also arise because of the dynamic nature of the ablation process. The coupling of the incident laser energy to the solid is a dynamic process which includes two highly nonlinear systems: the generation and

TABLE 2

METAL	DENSITY ρ (g/cm^3)	HEAT OF SUBLIMATION L (eV/atom)	THERMAL CONDUCTIVITY K(300K) (W/cm K)	HEAT CAPACITY C_p (cal/mole K)	Relative Damage Thresholds (Calculated from Eqn. 1) $(\kappa^{1/2}\rho L)/(\kappa^{1/2}\rho L)_{Al}$
Al	2.702	3.39	2.37	5.81	1.0
Cr	7.20	4.10	0.939	5.58	1.3
Ag	10.5	2.94	4.29	6.07	2.3
Cu	8.92	3.48	4.01	5.84	2.4
Rh	12.4	5.75	1.50	5.97	2.9
Mo	10.22	6.82	1.38	5.73	3.0
Au	19.31	3.81	3.18	6.06	3.4
			Uncommon Mirror Materials		
Hg	14.26	0.67	0.083	6.69	0.282
Te	6.25	2.23	0.02	6.14	0.318
Na	1.013	1.113	1.41	6.72	0.513

Table 2. Critical material parameters of some common and uncommon mirror materials.

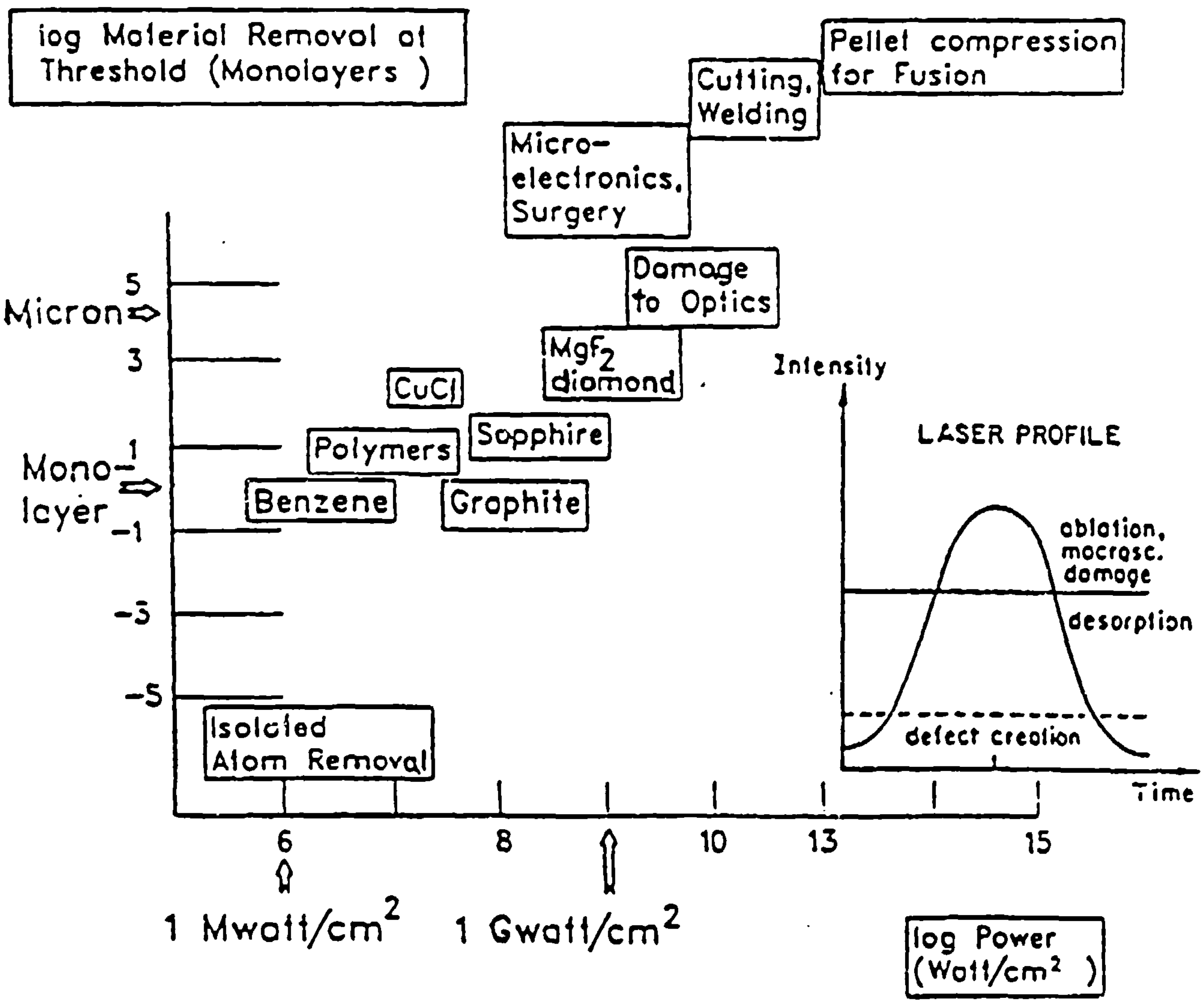

Figure 3. Material removal in units of monolayers as a function of laser pulse power density. Fields of application are indicated as well as a few substances of interest. The inset emphasizes the complexity of the interaction, i.e., the whole interaction scenario for a laser pulse.

avalanching of defects (Figure 3 inset) and the intrinsic nonlinear optical excitation ($n \cdot h\nu$) of a sequence of electronic transitions (e.g.,multiphoton photoemission). Each laser pulse runs through several orders of intensity (inset, Figure 3) and although the damage is usually dominated by the peak intensity, each laser pulse has the possibility of isolated atom removal and subsequent generation of surface defects. The defects are important because they serve as absorption centers for photons in the later part of the pulse and therefore, can rapidly multiply within one laser pulse. That defects can have a dramatic effect on the material ablation rate is demonstrated in the ablation of sapphire. The ablation rate of sapphire is increased by an order of magnitude (over the course of 10 pulses of 266 nm radiation with pulsewidths of 30ps) by the generation of surface defects.[21]

Further complicating the description of the ablation process is the plasma that can be generated at an irradiated surface. Laser-induced ablation in metals generally occurs at laser irradiances of about 10^5 to 10^6 W/cm^2 (at these energy densities, the time to ablate is 100 μsec to 10 msec).[22] Beginning as a predominately neutral vapor, the ejecta develop to include ions, electrons (i.e., a plasma), and larger clusters (even macroscopic particles) at power densities above 10^8 to 10^9 W/cm^2.[22] This plasma can be strong enough to serve as a source for the emission of soft x-rays and electrons.[23] The plasma is also a strong absorber of the incident laser radiation and can therefore, block the mirror surface from direct exposure to the incoming laser light. The development of a plasma and its energy feedback to the surface via re-radiation, electron sputtering, thermal conduction, and shockwave impact are all significant difficulties to be accounted for in modeling the ablation process.

LASER ABLATION THRESHOLD

In order for ablation to occur it is necessary to deposit sufficient energy at the surface of the material, in a short enough time, that a surface layer is removed/ejected before the deposited energy is thermally conducted away. That is, there is a laser power threshold below which material ablation does not occur. A rough estimate of the conditions necessary for laser ablation to occur is given by

$$\frac{E_p(1-R)}{(\kappa\tau)^{1/2}A\rho L} > 1, \tag{1}$$

where E_p is the total energy in the pulse, τ is the equivalent pulsewidth, A is an area parameter, R is the wavelength-dependent reflectivity, κ is the thermal diffusivity, ρ is the density, and L is the heat of sublimation.[24] When $E_p(1-R) = (\kappa\tau)^{1/2}A\rho L$, the threshold energy density for ablation of a material, E_{th}/A, is achieved, i.e., $E_p/A = E_{th}/A$. Thus, for a material to act as an effective optical fuse (or laser ablative mirror) at extremely low energy densities, it must have the following properties:

1. A low coefficient of thermal diffusivity, ($\kappa = K/(\rho C_p)$ where K is the thermal conductivity and C_p is the heat capacity at constant pressure). Note, for thin reflective layers, this low thermal diffusivity must also include the substrate.
2. Low density.
3. A low heat of sublimation or atomic binding energy.
4. A high absorption coefficient (i.e., low reflectivity) Note, this property need not be intrinsic to the reflector material; the absorptivity can be artificially enhanced.

Often, calculations are presented where it is assumed for simplicity that the relevant material parameters are independent of temperature.[23] This

assumption is only justified in certain cases. For example, it is known that the absorptivity (1-R) of copper at 10.6 μm changes from 0.008 at room temperature to approximately 0.025 near the melting point. Similar temperature dependent material property problems are encountered in thermal spike models of dense ion-produced cascades.[25] In this assessment report, we make the simplifying temperature-independence assumption.

Listed in Table 2 are the critical frequency-independent, intrinsic material parameters (items 1-3 above) of some common as well as some uncommon elemental metal mirror materials. In the last column of Table 2 we compare the frequency independent material properties responsible for determining the material ablation threshold to that of aluminum. It is clear from this that aluminum is one of the most favorable common mirror materials for use in the optical fuse system. However, entries in Table 2 for the relative ablation threshold have not accounted for the intrinsic reflectivity of the pure metals. The reflectivity of several of the common mirror materials is plotted versus wavelength in Figure 4 and tabulated in Table 3. Note that about half of the common mirror materials have intrinsic reflectivities above 70%, the lowest limit criterion, over the entire wavelength range measured, e.g., Ag, Al, and Rh.

Coupling the data in Figure 4 with the data in Table 2 suggests that even though the thermodynamic and physical properties are different, Ag can be made as suitable as Al as a mirror material. That is, a 500nm laser pulse incident on an Al mirror (intrinsic R~90%) and an Ag mirror (intrinsic R~95%) will begin to ablate at the same E_p/A and τ value if the Ag reflectivity is purposely spoiled to 90%. This is because a 5% decrease in reflectivity for Ag results in a factor of 2 increase in absorbed energy (or ablation

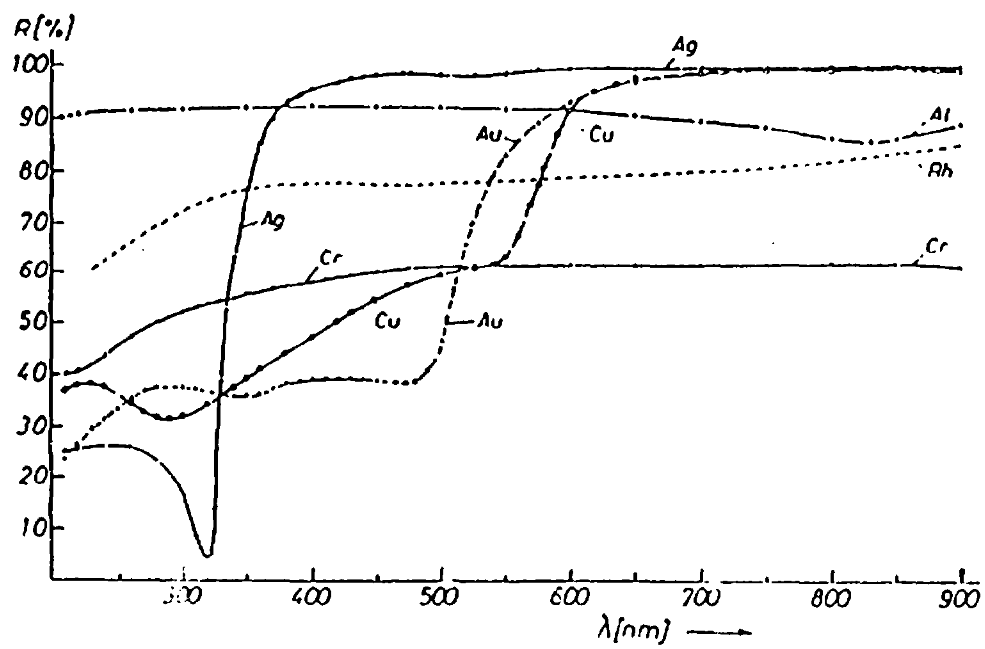

Figure 4. Reflectance of front surface mirrors of unprotected metal layers (at nearly normal incidence). Taken from ref. 26.

TABLE 3

Metal	Percent Reflectivity[a] $\lambda=10.6_{(\mu m)}$	$\lambda=1.06_{(\mu m)}$	$\lambda=0.50_{(\mu m)}$	$\lambda=0.26_{(\mu m)}$
Al	98.7	94.0	91.8	92.2
Cr	----	----	69.8	28.9
Ag	99.5	99.4	97.9	29.2
Cu	98.8	98.5	60.0	35.5
Rh	97.6	84.2	76.6	67.7
Au	99.4	98.6	47.7	35.6
Te	45.9	50.0	53.0	----

[a]The table entries for the common metals Al, Cr, Ag, Cu, Rh and Au are taken directly from the American Institute of Physics Handbook, 3rd Edition, McGraw-Hill Book Company, 1972. The tellurium data are estimates from a reflectivity graph found in The Physics of Selenium and Tellurium, W.C. Cooper (Ed.), Pergamon Press, 1967, page 14. Dashes indicate no reflectivity data was available.

Table 3. Percent intrinsic reflectance of several pure metal materials at several wavelengths.

efficiency) and the relative thresholds in Table 2 are about a factor of 2 different. In Table 4, the calculated laser-induced damage thresholds (LIDT) for pure, optically perfect mirror materials are given as a function of material reflectivity and in Table 5 as a function of the intrinsic reflectance at various wavelengths. Clearly, a balancing of the frequency independent critical material parameters and the reflectivity is necessary to achieve the best sacrificial mirror material.

Note that as a result of extremely low conductivity and binding energy, the uncommon mirror materials listed in Tables 2 - 5 appear to have the potential to be much more sensitive to ablation than aluminum, approaching the aforementioned maximum material damage threshold of 0.5 J/cm^2. Tellurium, in particular, appears very promising and future research investigations into the optical properties of its alloys with other metal mirror materials, or with absorption enhancers such as codeposited carbon, should be pursued. (Pure tellurium metal may be too intrinsically absorptive (i.e., 47% absorbed at 500 nm) to be used on its own as a mirror material (Table 3) except for optical systems used only at high ambient light levels, that is, bright daylight.) Based on the calculated threshold damage limit given in Table 4, mercury based alloys (amalgams) should also be examined in future research since they may have lower thresholds for ablation.

In comparing our calculated mirror material LIDTs (Equation 1, Table 3) with those reported in the literature (Table 1), we note a significant difference: our calculated values are approximately an order of magnitude larger. We believe this difference is due to our model of ablation being the result solely of classical absorption and thermalization, as discussed earlier in this section. We have not accounted for such effects as defect formation

TABLE 4

	LIDT (J/cm^2)[a]				
Metal	R=0.95	R=0.90	R=0.85	R=0.80	R=0.70
Al	20.4	10.2	6.8	5.1	3.4
Cr	18.6	9.3	6.2	4.7	3.1
Ag	23.0	11.5	7.7	5.7	3.8
Cu	32.2	16.1	10.7	8.1	5.4
Rh	29.8	14.9	9.9	7.5	5.0
Mo	32.6	16.3	10.8	8.1	5.4
Au	25.8	12.9	8.6	6.5	4.3
Hg	0.6	0.3	0.2	0.1	0.1
Te	0.8	0.4	0.3	0.2	0.1
Na	3.2	1.6	1.1	0.8	0.5

[a]LIDTs calculated using Equation 1 in the text, assuming a 1 nsec pulsewidth and the data entries of Table 2.

Table 4. Calculated LIDT for various metal mirror materials as a function of arbitrarily chosen reflectivities.

TABLE 5

Metal	LIDT (J/cm^2)[a,b] $\lambda=10.6_{(\mu m)}$	$\lambda=1.06_{(\mu m)}$	$\lambda=0.50_{(\mu m)}$	$\lambda=0.26_{(\mu m)}$
Al	78.6	17.0	12.5	13.1
Cr	----	----	3.1	1.3
Ag	229.8	191.7	54.7	1.6
Cu	134.2	107.4	4.0	2.5
Rh	62.1	9.4	6.4	4.6
Mo	125.2	5.4	4.1	2.5
Au	215.0	92.1	2.5	2.0
Hg	---	---	---	---
Te	0.1	0.1	0.1	---
Na	---	---	---	---

[a]LIDTs calculated using Equation 1 in the text, assuming a 1 nsec pulsewidth and the data entries of Table 2.

[b]A dashed entry in the table indicates that reflectivity data for that wavelength could not be found.

Table 5. Calculated LIDTs for various metal mirror materials as a function of the intrinsic reflectivity of the optically pure material at specific wavelengths.

and nonlinear excitations, which may have dramatic effects on the material ablation threshold.

LASER ABLATION ENERGY DEPENDENCE

Successful operation of the sacrificial mirror protection scheme requires that the optic path to the eye be rapidly destroyed due to the ablation of the thin film mirror during the first part of the initial laser pulse. Assuming the incident energy density at the mirror to be significantly greater than the threshold for ablation, the next condition for successful mirror operation is the complete ablation of the sacrificial mirror. Obviously, by making the mirror as thin as optically and mechanically possible, we lower the incident energy density necessary for complete mirror ablation. Therefore, this section determines an analytic expression for the maximum allowable mirror thickness as a function of incident wavelength and mirror material.

The laser ablation of material, by thermalization of absorbed laser energy, is strongly dependent on the mechanism of primary energy absorption. It is thought that the thermal effects observed in laser-impacted metals are driven by single photon absorption[27,28], although multiphoton absorption processes have been invoked for other laser-metal interactions.[29-33] The sequence of events leading to surface damage of metals is thought to be,[34,35]

Photon Absorption $\longrightarrow$ Thermal Expansion $\longrightarrow$ Melting $\longrightarrow$ Boiling $\longrightarrow$ Plasma.

This occurs during the course of a single pulse in a temporal sequence and across the spatial profile of a pulse for different energy densities (e.g., see inset Figure 3).

For heating achieved by single photon absorption the transmitted intensity (or inversely the attenuated intensity) of a uniform medium follows a Beer-Lambert exponential decay relation given by,

$$E(x)=E_{inc}e^{-\alpha x}, \qquad (2)$$

where $E(x)$ is the attenuated energy density at depth x into the material, E_{inc} is the incident energy density, and α is the absorption coefficient (or inverse of the absorption length). Assuming each layer, Δx, of the target will be ablated as long as the energy density is above the threshold,[36,37] or $E(x)>E_{th}$, the depth to which ablation occurs per pulse, is, from integrating Equation 2,

$$x=(1/\alpha)[\ln(E_{inc})-\ln(E_{th})]. \qquad (3)$$

From Equation 3 it is clear that the depth to which an individual laser pulse ablates the target is inversely proportional to α. On the other hand, the power density dependence varies more slowly as the logarithm of E_{inc}. Furthermore, for $E_{inc}\gg E_{th}$, the ablated layer has a hyperthermal (translational) energy distribution whereas for $E_{inc}\approx E_{th}$, the energy distribution of ablated material is closer to expected thermal evaporation energies (Figure 5).

A systematic investigation of pulse laser etching of a ceramic metal ($YBa_2Cu_3O_{7-\delta}$) is shown in Figure 6. The solid line is a fit from Equation 3

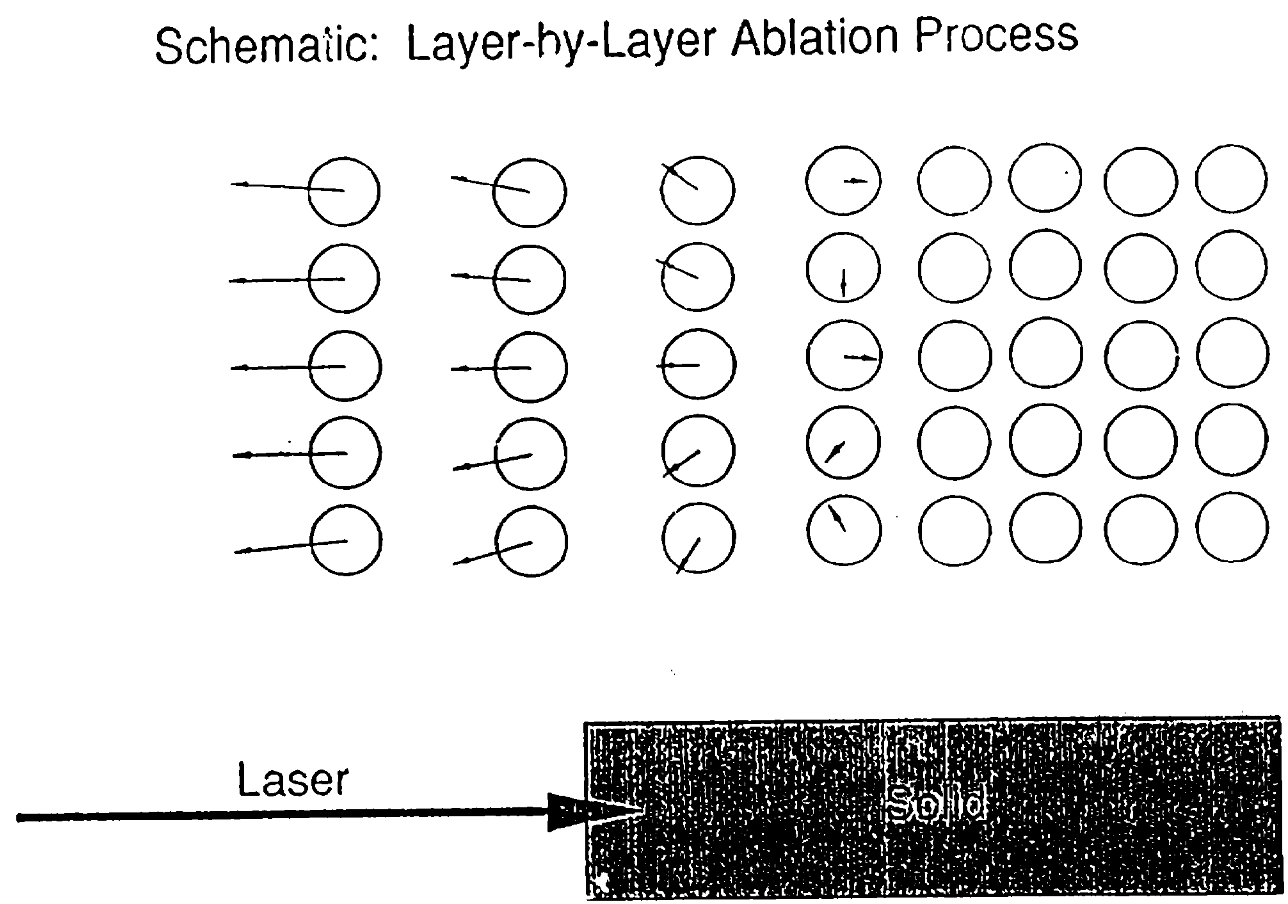

Figure 5. A schematic diagram detailing the ablation process. The circles represent layer components (atoms, molecules, solid clumps) and the arrows represent their respective energies. The inclosed section of the arrow represents the internal energy associated with that material component while the arrow section extending beyond the circle represents the additional translational energy the component possess.

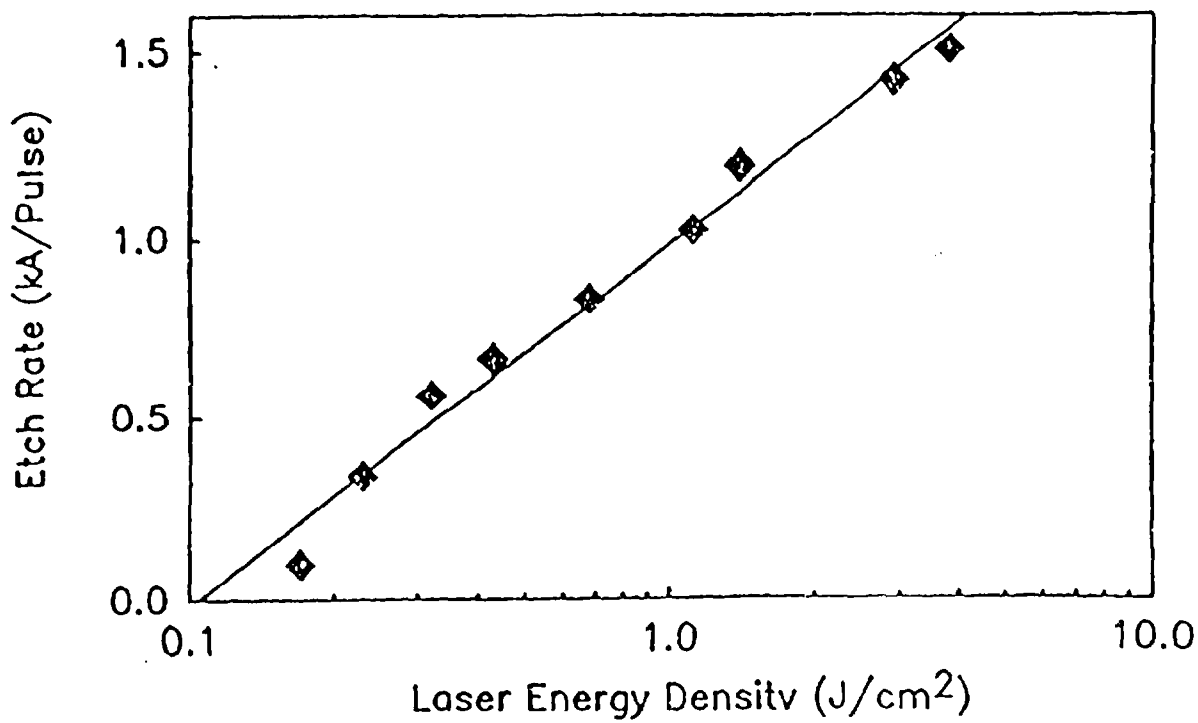

Figure 6. Etch rate per pulse of YBaCuO versus pulsed laser energy density.[36] The logarithmic dependence suggests a simple single photon driven ablation.

where E_{th} is determined from the x-intercept to be 0.11 $\mu J/cm^2$. This value of the ablation threshold agrees well with that determined by the novel photoacoustic deflection technique.[37,38] The logarithmic dependence of the etch rate in Figure 6 suggests a simple single photon driven ablation process like that derived in Equation 3.

Using measured values of α (Table 6) and calculated values of E_{th} for thin film mirror materials (Tables 4 and 5) and assuming an incident energy density of 0.5 $\mu J/cm^2$, the eye damage threshold, with an optical gain of 10^8 (considerably greater than our system design parameter), we estimate from Equation 3 the maximum mirror thickness, x_{max}, tolerated for successful mirror operation, i.e., mirror failure (Table 7). <u>None of the materials, in their pure and optically clean state, examined in this work will provide for successful operation of the device under the initial gain conditions assumed in this paper.</u> In Tables 7 and 8 we give the critical thicknesses as a function of wavelength for several different mirror materials at their intrinsic reflectivities and adjusted to 70% reflectivity by selective optical spoiling, respectively. It is clear from Table 7 that the mirror metals which have intrinsic reflectivities above our minimum standard (70%) allow for borderline successful operation of the device even with increased optical gain. The calculated thicknesses that would be removed by a laser pulse roughly correspond to the minimum thicknesses required for reasonable reflectivities (300 Å). The zero entries indicate that the mirror materials would not be removed under the conditions necessary for eye protection: the material damage threshold is greater than the incident light energy. Adjusting the mirror metals' reflectivities by "selective contamination" to 70% (Table 8) allows for thicker, more realistic coatings. In our

TABLE 6

Metal	α Absorptivity $(10^5/cm)$[a] $\lambda = 10.6_{(\mu m)}$	$\lambda = 1.06_{(\mu m)}$	$\lambda = 0.50_{(\mu m)}$	$\lambda = 0.26_{(\mu m)}$
Al	8.5	11.2	13.9	13.7
Cr	---	----	10.5	8.4
Ag	6.8	8.5	7.2	6.5
Cu	7.5	7.9	6.1	9.5
Rh	5.3	8.5	10.5	10.5
Au	8.5	7.6	4.6	7.6
Te[b]	10.0	10.0	10.0	10.0

[a] The table entries are calculated using $\alpha = (4\pi\kappa)/\lambda_o$ with the values for the extinction coefficient κ, as a function of wavelength, λ_o, taken from the American Institute of Physics Handbook, Third Edition, McGraw-Hill Book Company, 1972.

[b] Extinction coefficients were not available for Te and so an absorptivity value of 10^6 cm^{-1} was assumed.

Table 6. Intrinsic absorptivity of several pure and optically clean mirror materials.

TABLE 7

Metal	x_{MAX} (Å) $\lambda=10.6_{(\mu m)}$	$\lambda=1.06_{(\mu m)}$	$\lambda=0.50_{(\mu m)}$	$\lambda=0.26_{(\mu m)}$
Al	0	96	100	98
Cr	0	0	265	434*
Ag	0	0	0	530*
Cu	0	0	414*	315*
Rh	0	193	196	227*
Au	0	0	651*	424*
Te	622*	622*	622*	622*

* These values of x_{MAX} are based on an E_{th} from Table 5 where the materials intrinsic reflectivity is significantly less than 70%, the low limit criterion for mirror performance.

Table 7. Maximum mirror thickness based on material intrinsic reflectivity. The maximum mirror thicknesses are calculated using Equation 3 assuming an incident energy density of 0.5 $\mu J/cm^2$ and an optical gain of 10^8.

TABLE 8

Metal	x_{MAX} (Å) $\lambda=10.6_{(\mu m)}$	$\lambda=1.06_{(\mu m)}$	$\lambda=0.50_{(\mu m)}$	$\lambda=0.26_{(\mu m)}$
Al	247	193	169	161
Cr	---	---	---	434
Ag	293	234	280	---
Cu	229	228	---	---
Rh	340	240	206	---
Au	223	250	---	---
Te	---	---	---	---

Table 8. Maximum mirror thickness based on an induced material reflectivity of 70% The maximum mirror thicknesses are calculated using Equation 3 assuming a incident energy density of 0.5 $\mu J/cm^2$ and an optical gain of 10^8. Dashed table entries are for materials with intrinsic reflectivities less than the performance minimum, 70%.

calculations of these optically spoiled materials (i.e., artificially increased absorption, Table 8), we assume that a decrease in reflectivity results in a corresponding increase in absorptivity. For example, a 10% reduction in reflectivity results in a 10% increase in absorptivity. Note that of all the optically spoiled materials examined, aluminum is the only one which can respond over the entire visible and near-ir spectral ranges.

MIRROR FAILURE MODE

In the previous sections, we defined the important material parameters for laser induced damage and indicated how to improve material response. It is now necessary to determine how best to incorporate the mirror material into the eye protection device for maximum response, i.e., what is the optimum mirror design from a materials science perspective? We address this issue using aluminum, one of the better of the common mirror materials examined thus far (Table 1).

The removal of the reflective metal layer from the mirror substrate (front surface or back surface) will result in a disruption of the optic path. This removal may be affected by vaporization or in certain configurations, by melting or just surface roughening; the latter effects require considerably less absorbed energy than the former. For example, consider a simple thin aluminum reflective layer. To melt the layer requires energy to heat it to its melting point plus the enthalpy of fusion (for Al, 402 J/gram).[38] Volatilization requires an additional energy input to raise the temperature to the vaporization point plus the enthalpy of vaporization (for Al, 10,500

J/gram).[39] Assuming the irradiated spot on the mirror/fuse at the focal plane is less than 0.01 cm in diameter (a reasonable size for an optical system with a gain of 10^5-10^6), energy lost to radial thermal conductivity in the reflective layer as well as to radiative and convective cooling is negligible (to a first approximation). A general guideline for considering the importance of radial thermal conductivity in a laser irradiated target is that it is negligible if 4Kt is less than the diameter of the irradiated spot, where K is the thermal conductivity (ca. 2.37 W/cm K for aluminum)[39] and t is the laser pulse duration.[40] Thus, for spots less than 0.01 cm in diameter with pulses shorter than a microsecond, radial thermal conductivity in a thin reflective layer of aluminum may be neglected as a significant mechanism for energy loss.

Tabulated in Table 9 are the results of calculating the threshold irradiance <u>incident</u> (not absorbed) at a focal plane reflector required to melt or vaporize a mirror layer of aluminum which absorbs 10% of the incident radiation. 10% is chosen for convenience in this calculation. However, in a suitable device, absorbance values 2 to 3 times more than this are possible and would still provide acceptable optical properties for device operation. The absorptivity of the metal layer can be adjusted by incorporating controlled impurities (e.g. carbon particles or other metals) by vapor deposition, alloying or other techniques.

The thinnest layer of aluminum which makes a good mirror is about 200-500 nm[41]. Obviously, a free standing film would probably have to be thicker than this in order to support itself. From the data in Table 9, for aluminum, the trade off in thickness versus optical fuse failure threshold is a factor of about 5.7 in thickness (i.e., the difference between melting and

TABLE 9

REFLECTIVE LAYER	ALUMINUM
SUPPORT SUBSTRATE	NONE - FREE FILM
ASSUMPTIONS	NO THERMAL CONDUCTIVITY, RADIALLY OR IN DEPTH; SQ.ROOT OF 4 AT LESS THAN FOCUSSED SPOT SIZE FOR OPTICAL GAINS 10 TO 5 OR 6 WITH 1 INCH LENS AND PULSE WIDTHS LESS THAN 50 NSEC OR SO REFLECTIVITY "SPOILED" TO GIVE DESIRED VALUE
FRACTION RADIATION ABSORBED	0.1 (I.E., 1-FRACTION REFLECTED)
DENSITY REFL. LAYER (gm/cc)	2.7
MELTING TEMP DEG. C	660
VAPORIZATION TEMP. DEG. C	2327
AMBIENT TEMP. DEG. C	25
HEAT CAPACITY SOLID (J/gm-C)	0.901
HEAT CAPACITY MELT (J/gm-C)	1.08
HEAT OF FUSION (J/g)	402
HEAT OF VAPORIZATION (J/g)	10500
OPTICAL GAIN OF DEVICE	1.00E+05

THRESHOLD TO MELT J/cm^2	THICKNESS nm	INCIDENT FLUENCE J/cm^2	HEAT TO MP J/cm^2	MELTING J/cm^2	HEAT TO BP J/cm^2	VAPORIZE J/cm^2	TOTAL TO VAPORIZE J/cm^2
0.0827	50	0.8267	0.0772	0.0054	0.2430	0.1418	0.4675
0.1157	70	1.1573	0.1081	0.0076	0.3403	0.1985	0.6544
0.1488	90	1.4880	0.1390	0.0098	0.4375	0.2552	0.8414
0.1653	100	1.6533	0.1545	0.0109	0.4861	0.2835	0.9349
0.2480	150	2.4800	0.2317	0.0163	0.7291	0.4253	1.4024
0.2811	170	2.8106	0.2626	0.0165	0.8264	0.4820	1.5894
0.3307	200	3.3066	0.3090	0.0217	0.9722	0.5670	1.8699
0.4960	300	4.9599	0.4684	0.0326	1.4583	0.8505	2.8048
0.8267	500	8.2665	0.7724	0.0543	2.4305	1.4175	4.6746
1.1573	700	11.5731	1.0813	0.0760	3.4027	1.9845	6.5445
1.3226	800	13.2264	1.2358	0.0868	3.8888	2.2680	7.4794
1.6533	1000	16.5330	1.5448	0.1085	4.8610	2.8350	9.3493
8.2665	5000	82.6652	7.7238	0.5427	24.3049	14.1750	46.7464
16.5330	10000	165.3305	15.4476	1.0854	48.6097	28.3500	93.4928
24.7996	15000	247.9957	23.1715	1.6281	72.9146	42.5250	140.2391
33.0661	20000	330.6609	30.8953	2.1708	97.2194	56.7000	186.9855
41.3326	25000	413.3261	38.6191	2.7135	121.5243	70.8750	233.7319
41.9939	25400	419.9393	39.2370	2.7569	123.4687	72.0090	237.4716

Table 9. Calculated incidence irradiances required to melt and/or vaporize a mirror layer of aluminum which absorbs 10% of the incident radiation.

vaporizing). The question to be addressed here is, can the melting of a free standing reflective film only ca. 10^{-3} cm in diameter compete with vaporization of a ca. 300 nm thick reflective layer on a substrate?

Assuming an input energy of 0.5 J/cm^2 onto an aluminum mirror surface which has been modified to achieve 70% reflection, results an energy absorption of 0.15 J/cm^2. Defining a 10^{-3} cm diameter focal spot size and assuming a 300 nm thick free standing aluminum film results in a final temperature of only 166 K (assuming a density of 3 g/cm^2 and heat capacity of 1 J/gm-C), which is not enough to even melt the aluminum. Therefore, device designs incorporating mirror melting schemes do not appear feasible for eye protection using common elemental mirror materials. Other, more novel mirror materials may work in such a system but need to be reviewed on a case by case basis.

TIME RESPONSE OF FAILURE

One device/material area that has not been addressed in this report involves the response time of the material-vaporization. That is, although materials may exist that will vaporize at the required thresholds, will they vaporize quickly enough to provide protection against the first incident laser pulse? Order of magnitude studies of the kinetics of the ablation of some materials have been reported suggesting nsec vaporization times.[42,43] However,

these studies are usually conducted on relatively thick samples (100's of microns) and under conditions of ultra-high vacuum which are not acceptable for a deployable, eye protection device. (Although, the focal plane mirror system could be sealed in a transparent vacuum cell should such prove advantageous.) Extensive investigations of the kinetics of the ablation of potential metal mirror materials under more realistic environmental conditions and with thinner samples are required before a definitive answer on the response time of material vaporization can be obtained.

CONCLUSION

The minimum material damage threshold for complete eye protection is <0.5 J/cm^2 using our generic device design. The thermodynamically best film identified in this report, for use as an ablative mirror "fuse" system, aluminum, has a measured intrinsic minimum damage threshold for the optically pure reflector of 8 J/cm^2 for laser radiation at $\lambda = 0.492$ microns with a pulsewidth of 500 nsec (Table 1). Based on this measured response and our calculated values of mirror material removal (Tables 7 and 8), we conclude that, from a materials science perspective, the sacrificial mirror eye protection system, using intrinsically reflective optically pure aluminum is borderline feasible with respect to protection against pulsed lasers with pulse durations less than about 10 nsec and average energies per pulse in excess of 0.5 μJ/cm^2. This conclusion is in general agreement with experimental measurements on sacrificial mirror devices reported by the Harry Diamond Laboratory.[44] In their work, 10 to 20 nm vacuum deposited metal films

on black substrates were studied. In general, they observed mirror failures (20% reflective mirrors) in the range 0.1-1 J/cm^2, 1-10 J/cm^2 and 10^3-10^4 W/cm^2 for Q-switched, normal pulsed and CW cases respectively.[44]

Several material variables which may be adjusted in order to assist in reducing the failure threshold of a chosen mirror/fuse material have been identified in this report. For example, the calculations in Table 9 are for aluminum with a normal absorption of 10%, adjusted by controlled optical spoiling (contamination) of the reflective surface. This could be increased a factor of 2 or more and still meet minimum acceptable optical requirements for certain field applications. This optical spoiling lowers the threshold for mirror ablation into a range close to that required for a suitable eye protection system if laser pulses are longer than 10 nsec and less than 0.5 μJ/cm^2. However, the amount of material removed with just one pulse (Tables 7 and 8) is borderline with respect to the destruction of a realistic thin film - even with spoiling to 70% reflectivity and increased optical gain.

The choice of mirror material has also been addressed and is certainly not limited to aluminum, although this appears to be the best of the common mirror materials examined (Table 1). Several unique reflective materials with the potential for enhanced sensitivity have been identified.

PROPOSED FUTURE AREAS OF RESEARCH

In reviewing the operation and design of the sacrificial mirror system, potential areas for future material research efforts were also suggested. One of the more obvious areas included examinations of air sensitive materials.

That is, if the reflective layer could be sealed in a small vacuum or gas filled cell, the use of materials which may otherwise oxidize is possible. This could allow for the use of certain alloys and amalgams which may be more thermodynamically sensitive than "elemental" metals. The reflective system also need not be limited to metals. Numerous inorganic polymers exist which themselves may be sufficiently metal-like to be suitable reflectors and which may have intrinsically low thresholds for thermal damage. One such example is $(SN)_x$. Unfortunately, there is only limited information available on such inorganic systems and a conclusive assessment of their potential at this time can not be made.

A unique research concept that was developed during the course of this work is lowering the threshold for fuse failure by placing a thin layer of material (probably a polymer or certain inorganic crystal systems) having a very low thermal stability between the substrate and the thin reflective layer. Thermal shock, produced by partial absorption of laser energy, could produce rapid decomposition of this interstitial layer thus "blowing off" the reflective layer. Such a system could be designed for irradiation either through a transparent substrate and the partially absorbing decomposing layer, which lies between the substrate and the mirror layer (back surface mirror system), or as a front surface mirror, with partial absorption by the reflector resulting in heat transfer (thermal shock) to the decomposing layer below. Numerous polymer coatings can be envisioned with low thermal stabilities as well as a variety of inorganic crystals. Inorganic crystals exhibiting rapid decomposition with low and distinct temperature or thermal shock thresholds include the monovalent metal azides, fulminates, and ammonium permanganates and halates. The small area required to be coated with these

less stable materials (10^{-3} cm diameter spot at the focal point) will limit the amount of excess energy liberated during optical fuse failure. Such a thermochemically assisted system may considerably reduce the response time and energy threshold for fuse failure below that for a free standing metal reflector and should be investigated.

IMPORTANT AREAS OF OPTICAL DESIGN

During the course of this evaluation of materials for use in ablative mirror based systems, various important aspects of the optical design also had to be considered. In many instances we made educated assumptions about the device system in order to assess material properties. However, other aspects of the optic system which we did not discuss need to be addressed in any proposed design. For example, the angle of incidence that the light makes with the ablative mirror will affect the optical gain measured at the mirror surface. In addition, questions about the quality of the reconstruction of the visual scene after it has been focussed into a small spot remain unanswered. Furthermore, how optically flat does the mirror need to be in order to give undistorted images and what are realistic fields of view, optical gains and light gathering (f-values) abilities of portable lens systems? These are examples of important device parameters that need to be clearly addressed before an accurate assessment of the ablative-mirror concept can be prepared.

One additional area of concern involves the energy distribution profile of the focussed light and its interaction with the mirror material. Because

the focussed light has a spatial intensity gradient, for example, gaussian, it may be that only the central portion of the focal spot will exceed the threshold and result in clean ablation of the mirror surface with the edges of the focal spot not cleanly ablated. It is not clear how extensive the damage to the edges of the focal spot will be or how the damage will affect the light throughput to the eye or sensor. These are aspects of the ablative mirror device operation that can be addressed best by experiment. It is important to note, however, that a material with a lower damage threshold than the eye would make this problem moot. Any light getting through to the eye would be below the eye damage threshold.

APPENDIX I

Ablative Mirror Concept as CW Protection

Eye and material damage thresholds for CW irradiation are significantly different from the corresponding pulsed irradiation values indicated in the main body of this report. The differences arise because of the variations in the rate at which energy is introduced to the system in the two cases. During pulsed irradiation, energy is introduced so quickly that the deposited energy can not be thermally conducted away, resulting in material ablation at relatively low thresholds. In the case of CW irradiation, the same amount of energy is deposited but in a longer period of time, allowing for some dissipation of the deposited energy. Because of the thermal conduction, larger radiant exposures can be tolerated before damage occurs. In this appendix, the ability of the ablative mirror concept to protect eyes/sensors from continuous wave (CW) irradiation is assessed.

The maximum permissible exposure (MPE) for ocular viewing in the visible and near infrared spectral regions is given by

$$MPE = 1.8t^{3/4} \times 10^{-3}\ J/cm^2 \qquad (I.1)$$

for exposure times, t, greater than 10^{-4}sec. These exposure limits are significantly different than the 0.5 $\mu J/cm^2$ limit imposed for submicrosecond exposures. For our analysis, we assume a maximum exposure time of one (1) second (involuntary blinking and head turning are assumed to be sufficient protection schemes for longer exposures) which results in a radiant exposure limit of 1.8 mJ/cm^2.

Using the one second exposure limit, the laser-induced-damage thresholds (LIDT) for various mirror materials have been recalculated and are presented in Table I-1. These thresholds are calculated using the previously derived Equation 1, the intrinsic reflectivities of the pure material and the material parameters given in Table 2. Using the assumed optical gain of 10^6 for the mirror device optics, the required incident laser-induced-damage threshold can be calculated. This threshold represents the minimum amount of radiant energy that must enter the mirror device's optical system in order to induce ablative damage to the mirror material. In Figure I-1 the incident LIDT for several mirror materials (at their intrinsic reflectivities) are compared with the maximum permissible ocular exposure (calculated from equation I.1) over a wide range of exposure times. The only mirror material that approaches the required response without artificially increasing its absorptivity is tellurium. Unfortunately, tellurium has an intrinsic reflectivity of 53% which exceeds our initially assumed minimum device operating parameter of 70% reflectivity.

As in the pulsed irradiance case discussed in the main body of this report, the mirror material response can be improved by optical spoiling (contaminating) the intrinsic material reflectivity (Table I-2). In Figure I-2, the incident LIDT of aluminum at various reflectivities is compared with the eye damage thresholds over a wide exposure duration range. Clearly, the material response is not adequate to protect the eye under the initially assumed device performance parameters. Note that as the exposure duration and the material reflectivity decrease, the damage thresholds for the eye and the

TABLE I-1

Metal	LIDT (J/cm^2)[a,b] $\lambda=10.6_{(\mu m)}$	$\lambda=1.06_{(\mu m)}$	$\lambda=0.50_{(\mu m)}$	$\lambda=0.26_{(\mu m)}$
Al	2.5×10^6	5.4×10^5	3.9×10^5	4.1×10^5
Cr	----	---	9.8×10^4	4.2×10^4
Ag	7.3×10^6	6.1×10^6	1.7×10^6	5.1×10^4
Cu	4.2×10^6	3.4×10^6	1.3×10^5	7.9×10^4
Rh	2.0×10^6	3.0×10^5	2.0×10^5	1.5×10^5
Mo	3.9×10^6	1.7×10^5	1.3×10^5	7.9×10^4
Au	6.8×10^6	2.9×10^6	7.9×10^4	6.3×10^4
Hg	---	---	---	---
Te	3.2×10^3	3.2×10^3	3.2×10^3	---
Na	---	---	---	---

[a]LIDTs calculated using Equation 1 in the main text, assuming a 1 second exposure time and the data entries of Table 2.

[b]A dashed entry in the table indicates that reflectivity data for that wavelength could not be found.

Table I-1. Calculated LIDTs for various metal mirror materials as function of the intrinsic reflectivity of the optically pure material at specific wavelengths. To convert these LIDTs to the minimum incident LIDTs, simply divide by the assumed optical gain of the ablative mirror device, 10^6.

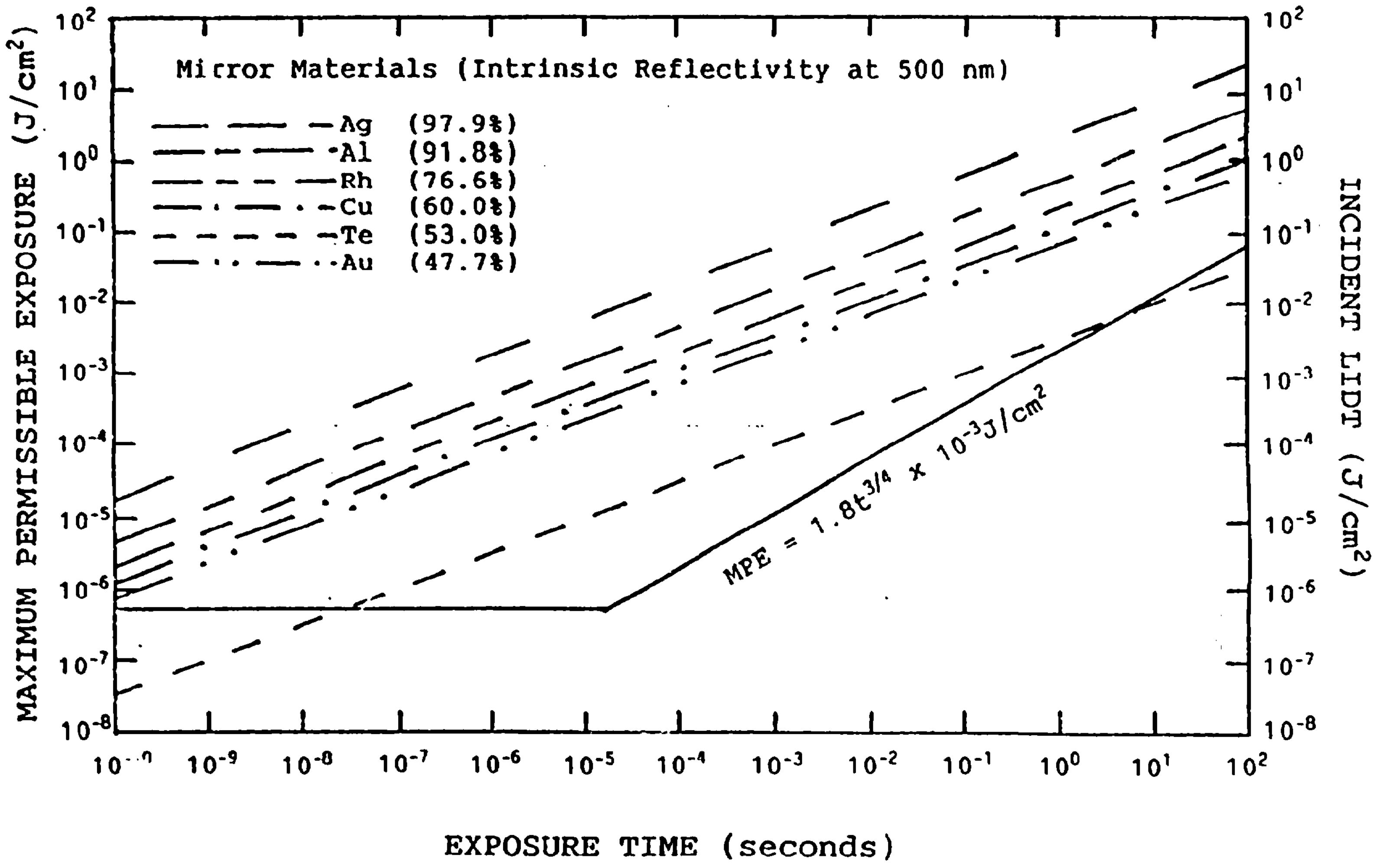

Figure I-1. The incident LIDTs for several mirror materials (at their intrinsic reflectivities at 500 nm) are compared with the American National Standard Institute (ANSI) maximum permissible exposure (MPE). The incident LIDTs are calculated by dividing the material LIDT by the assumed optical gain of the ablative mirror device, i.e., 10^6.

TABLE I-2

Metal	LIDT (J/cm^2)[a] R=0.95	R=0.90	R=0.85	R=0.80	R=0.70
Al	6.5×10^5	3.2×10^5	2.2×10^5	1.6×10^5	1.1×10^5
Cr	5.9×10^5	2.9×10^5	2.0×10^5	1.5×10^5	9.8×10^4
Ag	7.3×10^5	3.6×10^5	2.4×10^5	1.8×10^5	1.2×10^5
Cu	1.0×10^6	5.1×10^5	3.4×10^5	2.6×10^5	1.7×10^5
Rh	9.4×10^5	4.7×10^5	3.1×10^5	2.4×10^5	1.6×10^5
Mo	1.0×10^6	5.1×10^5	3.4×10^5	2.6×10^5	1.7×10^5
Au	8.2×10^5	4.1×10^5	2.7×10^5	2.1×10^5	1.4×10^5
Hg	1.9×10^4	9.5×10^3	6.3×10^3	3.2×10^3	3.2×10^3
Te	2.5×10^4	1.3×10^4	9.5×10^3	6.3×10^3	3.2×10^3
Na	1.0×10^5	5.1×10^4	3.5×10^4	2.5×10^4	1.6×10^4

[a]LIDTs calculated using Equation 1 from the main text, assuming a 1 second exposure and the material data entries of Table 2.

Table I-2. Calculated LIDTs for various metal mirror materials as function of arbitrarily chosen reflectivities. Reflectivity of a given mirror may be reduced (i.e., absorption increased) by "artificial selective contaminations" below that of the intrinsic reflectivity of the optically pure material as shown in Table I-1 and Figure I-1. To convert the calculated LIDT above into the incident LIDT, divide by the assumed optical gain of the ablative mirror device, i.e., 10^6.

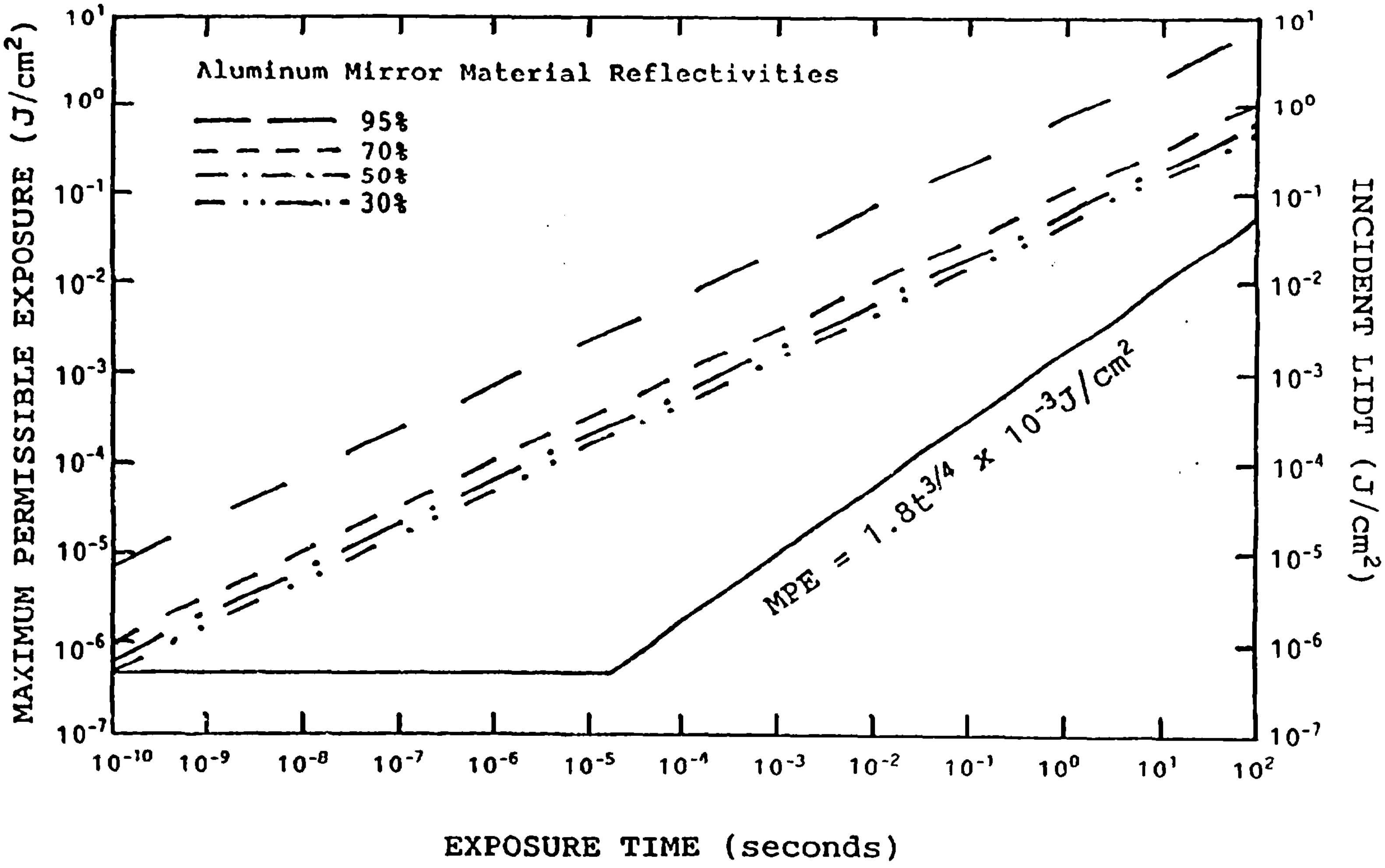

Figure I-2. The incident LIDTs of an aluminum mirror at arbitrarily chosen reflectivities are compared with the American National Standard Institute (ANSI) maximum permissible exposure (MPE). The incident LIDTs are calculated by dividing the material LIDT (Table I-2) by the assumed optical gain of the ablative mirror device, i.e., 10^6. The reflectivity of a given mirror material may be reduced (i.e., absorption increased) by "artificial selective contaminations" below that of the intrinsic reflectivity of the optically pure materials.

mirror approach until at, 30% reflectivity and one nanosecond exposure, they nearly intersect. Below this point, eye protection will be afforded by the mirror material. However, at this critical point, the mirror material performance characteristics are below the minimum initially assumed in this analysis, i.e., a minimum reflectivity of 70%.

In conclusion, the damage thresholds for common mirror materials, under the conditions of continuous wave irradiation, are too great to afford adequate eye protection. This conclusion is based on the device operating constraints detailed in the main body of this report. As with the pulsed irradiation case, several material parameters have been identified which may assist in reducing the mirror material failure threshold.

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